Accepted Manuscript:

Kinematics of knees with osteoarthritis show reduced lateral femoral roll-back and maintain an adducted position. A systematic review of research using medical imaging.

1. Scarvell, Jennie M. PhD, B(App)Sc
   - University of Canberra, Australia
   - Canberra Hospital, Australia.

   jennie.scarvell@canberra.edu.au
2. Galvin, Catherine R, B ElectEng (hons), BSpExSc (hons)
   - University of Canberra, Australia

   Catherine.galvin@canberra.edu.au
3. Perriman, Diana M. PhD, MPhil, B(App)Sc
   - Canberra Hospital, Australia.
   - Australian National University, Australia
   - University of Canberra, Australia

   diana.perriman@act.gov.au
4. Lynch, Joseph T, MSc, BSc
   - Canberra Hospital, Australia.
   - Australian National University, Australia

   joe.lynch@act.gov.au
5. van Deursen, Robert W.M. PhD, MSc, B(App)Sc.
   - Cardiff University, United Kingdom
   - Arthritis Research UK Biomechanics and Bioengineering Centre, Cardiff, UK

   vandeursenr@cardiff.ac.uk

Corresponding author
Prof Jennie Scarvell
Email: jennie.scarvell@canberra.edu.au;
Phone: +61 2 6206 8710, +61 2 6201 2796; mobile: +61 410 212 806
Post: 12 D 35 Faculty of Health, University of Canberra, Bruce ACT 2601
Fax: +61 2 6201 2527

Accepted - Journal of Biomechanics, Elsevier. 8 May 2018

Title

Kinematics of knees with osteoarthritis show reduced lateral femoral roll-back and maintain an adducted position. A systematic review of research in medical imaging.

Abstract

Background: While several studies describe kinematics of healthy and osteoarthritic knees using the accurate imaging and computer modelling now possible, no systematic review exists to synthesise these data. **Method:** A systematic review extracted quantitative observational, quasi-experimental and experimental studies from PubMed, Scopus, Medline and Web of Science that examined motion of the bony or articular surfaces of the tibiofemoral joint during any functional activity. Studies using surface markers, animals, and in-vitro studies were excluded. **Results:** 352 studies were screened to include 23 studies. Dynamic kinematics were recorded for gait, step-up, kneeling, squat and lunge and quasi-static squat, knee flexion in side-lying or supine leg-press. Kinematics were described using a diverse range of measures including six degrees of freedom kinematics, contact patterns or the projection of the femoral condylar axis above the tibia. Meta-analysis of data was not possible since no three papers recorded the same activity with the same measures. Visual evaluation of data revealed that knees with osteoarthritis maintained a more adducted position and showed less posterior translation of the lateral femoral condylar axis than healthy knees. Variability in activities and in recording measures produced greater variation in kinematics, than did knee osteoarthritis. **Conclusion**: Differences in kinematics between osteoarthritic and healthy knees were observed**,** however, these differences were more subtle than expected. The synthesis and progress of this research could be facilitated by a consensus on reference systems for axes and kinematic reporting.

1. Introduction

Osteoarthritis of the knee affects 18.2% of people in the UK over 45 years, which was 4.11 million people in 2017 (Arthritis Research UK 2017). In Australia, total knee replacement is the most common surgical procedure requiring hospital admission (Australian Institute of Health and Welfare 2015). With osteoarthritis imposing such a heavy burden of disease, there is intense interest in evidence-based solutions.

Much of the current understanding of knee kinematics in osteoarthritis is due to research using motion and kinetic analysis. Disease progression has influenced temporospatial characteristics of gait (Kaufman et al. 2001, Zeni et al. 2009); and increased adductor moment (Hurwitz et al. 1999, Andriacchi et al. 2006), varus thrust (Sharma et al. 2001) and muscle co-contraction have been validated as predictors of progression (Lewek et al. 2004, Hodges et al. 2016). These insights have informed current non-surgical management approaches (Simic et al. 2011, Fregly 2012, Farrokhi et al. 2013). However, a recent systematic review did not find evidence of increased knee adduction moment nor loss of internal rotation, demonstrating that aspects of kinematics in osteoarthritis still need explanation (Mills et al. 2013).

Recently, advances in medical imaging and computerised reconstruction have facilitated visualisation and modelling of the articular surface thereby ushering in the next generation of kinematic analysis. In its earliest form, roentgen photogrammetric analysis (RSA) using biplanar x-ray was highly accurate but invasive, consequently its application was constrained to surgical participants in small numbers (Karrholm et al. 2000, Saari et al. 2005, Weidow 2006). More recently CT and MRI have been used to provide a 3-dimensional model, which when registered to fluoroscopy, provides 4-dimensional analysis (Li et al. 2005, Hamai et al. 2009, Pickering et al. 2009, Koga 2015). Fluoroscopy units are now capable of capture rates of up to 250 frames per second (You et al. 2001) and image registration algorithms can provide precision of less than one millimetre and one degree (DeFrate et al. 2006, Akter et al. 2015, Zeighami et al. 2017). Computer algorithms for 4D CT are also being developed (Alta et al. 2012). In this environment, previously unavailable accuracy in joint-level kinematics is emerging.

It is therefore timely to review whether current computational imaging can define the kinematic characteristics of osteoarthritis at the articular surface level (arthrokinematics). Individual studies have reported reduced flexion range of motion in addition to reduced posterior translation of the femoral condyles across the tibial plateau associated with flexion (Saari 2005, Scarvell et al. 2007). But there is a lack of agreement (Saari 2005, Hamai 2009) and the information has not been gathered into a cohesive review to identify the specific characteristics of joint movement in knee osteoarthritis.

This systematic review therefore asks what are the characteristics of arthrokinematics of the knee with osteoarthritis that deviate from healthy knee kinematics.

2. Method

This study was designed according to PRISMA guidelines and registered with Prospero (CDR42017072481) prior to commencement (Box 1).

Studies were identified by searching Medline, Web of Science, Pub Med, and Scopus. The reference lists of identified papers were further searched for eligible papers. Studies that were eligible included joint surface level kinematics descriptions of knees with osteoarthritis published or 'in press' (Box 2). Studies using surface markers, in-vitro, animals, and papers that did not include new data were excluded.

To capture knee arthrokinematics rather than motion analysis from skin marker systems, search terms were designed to identify the new technologies and bone and soft tissue imaging modalities used in joint kinematics research.

Osteoarthrit* AND *knee* AND *kinemat* AND

(fluoroscop* OR regist* OR ultrasound OR 'dynamic MRI').

There were no limits placed on the search, including publication date, language, document type, or age of participants.

2.1 Study selection

Each step of study selection, the assessment of quality and the determination of study design was conducted independently by two authors, blind to each other's findings. Differences were resolved by discussion (Figure 1).

2.2 Methodological quality

A Modified Downs and Black checklist (Downs et al. 1998) was developed for assessment of quality, guided by the Cochrane Assessment of Bias (Higgins et al. 2011), with focus on internal validity and internal bias. Checklist items were grouped into reporting, external validity, internal validity (bias), internal validity (selection bias) and statistical power (Table 1). A score was not used (Higgins 2011), since this review intended to be inclusive of all available studies in this new field, therefore methodological quality was not an inclusion criterion.

2.3 Data extraction

Data were extracted to determine the study designs, the characteristics of the healthy and osteoarthritic populations, the interventions in terms of the functional activity the participants performed and the measurement systems that were used.

Kinematic data were extracted for osteoarthritic and healthy knees for comparison where available. These data were extracted from tables or, where only figures were available, data extraction was performed using a bespoke Matlab routine (Mathworks, Natick, Massachusetts). Data were tabulated for each 15-degree interval from 0 to 150 degrees of knee flexion. Where 'maximum flexion' was reported, but not the actual flexion value, these data were not included, as they could not be mapped against flexion. Where an experimental group included participants with and without osteoarthritis, authors were contacted. For a study on the effect of obesity on knee kinematics (Li et al. 2017), authors provided population data (mean and standard deviation) for the participants with osteoarthritis separately.

2.4 Synthesis of results

To determine whether there was adequate study homogeneity for meta-analysis, we decided that more than two studies should meet the following criteria:

Like kinematic measures reported

Like activities (tasks) performed by participants

Like knee compartment affected by osteoarthritis

If meta-analysis was not performed, synthesis was to be conducted using graphical presentation of the data, for descriptive interpretation.

3. Results

3.1 Study selection

Database searching retrieved 352 papers, after removal of duplicates, screening and addition from reference lists 23 papers were included (Figure 1, Table 1, (Saari 2005, Weidow 2006, Scarvell 2007, Hamai 2009, Kitagawa et al. 2010, Yue et al. 2011, Farrokhi et al. 2012, Sharma et al. 2012, Kawashima et al. 2013, Mochizuki et al. 2013, Farrokhi et al. 2014, Fiacchi et al. 2014, Haladik et al. 2014, Kitagawa et al. 2014, Mochizuki et al. 2014, Gustafson et al. 2015, Li et al. 2015, Mochizuki et al. 2015, Dimitriou et al. 2016, Farrokhi et al. 2016, Hamai et al. 2016, Li 2017, Zeighami 2017)).

3.2 Quality and risk of bias within studies

A key strength of papers was quality of reporting (Table 1), especially stating aims and outcome measures. The study designs were weak in control of bias, internal validity and sufficient power to detect a minimum clinically important difference (Table 1). External validity was not reported in any of the papers. Only seven studies had a contemporaneous control group, and just five were matched for age and gender and none for body mass index (BMI). Furthermore, only five papers used statistical analyses that were capable of adjustment for repeated measures or confounding variables, and just one paper was powered sufficiently to detect a clinically important difference (Haladik 2014).

3.3 Characteristics of studies

There were no meta-analyses retrieved, 18 quasi experimental papers, and five descriptive studies (Table 2). Sample sizes were generally small (mean osteoarthritis n=12; mean control group n= 13.25). Participants had predominantly advanced-stage medial-compartment osteoarthritis. One paper analysed medial and lateral osteoarthritis as a variable (Farrokhi 2012), and one included lateral compartment only (Weidow 2006). Participants with osteoarthritis were generally older (mean ages of 68, matched control group mean 48, and non-matched mean age 26 years).

Technologies used to measure arthrokinematics included fluoroscopy (single- or dual-plane) of the activity and either CT or MRI of the knee, or bi-planar x-ray. Dual-plane fluoroscopy solves issues with out-of-plane translation error, but adds radiation and smaller field of view (Fregly et al. 2008, Scarvell et al. 2008). Three-dimensional CT or MRI may be registered to the fluoroscopy to generate a 4-dimensional dynamic model and derive arthrokinematic data.

3.4 Kinematics in 6-degrees of freedom

Nine studies analysed kinematics in 6-degrees of freedom (Table 2). All nine reported knee flexion and internal/external rotation and six reported all 6-degrees of freedom. One paper reported variability between stable and unstable osteoarthritic knees, but not original data. The range of activities included gait, loading phase of downhill walking, stepping, step-up and lunge and quasi-static squat and knee flexion position with the foot on a step.

Synthesis:

Not more than two papers reported the same activity, so meta-analysis was not performed. Overall, the data for knees with osteoarthritis did not stand apart from the healthy knees. The data plots demonstrated that without exception, healthy and osteoarthritic knees exhibit concurrent tibial internal rotation with flexion (Figure 2). Some groups with osteoarthritis lacked 5-degrees of terminal knee extension (Figure 2, 3). In four of five studies with a contemporaneous control group, the osteoarthritic knees had less rotation than the healthy knees with only Zeighami 2017 reporting more rotation during a quasi-static squat activity.

Knees with osteoarthritis tended to be more adducted than the healthy knees, but without a clear pattern of abduction/adduction associated with flexion (Figure 3). An exception, in which osteoarthritic knees were more adducted than the healthy knees, was in flexion beyond 90 degrees (90 to 105 degree lunge) (Yue 2011).

3.5 Contact patterns

Eleven papers analysed arthrokinematics as femur on the tibial plateau contact patterns (Table 2). One paper reported contact pattern by percentage of the gait cycle, rather than knee flexion (Haladik 2014). One paper reported data variability only (Gustafson 2015). The activities recorded by the remaining nine studies were lunge, downhill walking, step-up, chair-rise, open-chain leg extension, supine leg-press, quasi-squat, squat and kneeling. While three papers reported lunge, one included participants with rheumatoid arthritis and extraction of osteoarthritis data were not possible (Kitagawa 2014).

Analysis of these data required the tibial-plateau origin to be established and the size of the knee to be normalised. The origin was defined by either bisecting the line drawn between the most medial and lateral points (Farrokhi 2016), a line between the centres of circles fitted to the tibial articular surfaces (Li 2015, Zeighami 2017), or the distance from the posterior rim of the tibial plateau (Scarvell 2007). Normalisation was reported in four studies only. One paper reported data as a percentage of the tibial plateau (Li 2015). To plot these, we converted percentages to millimetres according to Zeighami 2017.

Synthesis:

Criteria for meta-analysis were not met. The heterogeneity of AP-translation data origins meant that the positions on the y-axis could not be interpreted; only the patterns and slopes could be compared visually. The contact patterns for the medial-femoral condyle on the tibial plateau for healthy knees moved posteriorly during flexion in a quasi-static squat and leg-press but anteriorly in downhill gait (Figure 4). For knees with osteoarthritis the contact patterns moved anteriorly during flexion for chair-rise, open-chain leg extension and step-up but posteriorly for squat leg-press and kneel and stayed relatively stationary for step-up, downhill walking and lunge. Of the studies with a control group, the medial contact pattern for knees with osteoarthritis was usually more anterior to the healthy knees (Scarvell 2007, Farrokhi 2016).

The contact patterns for the lateral-femoral condyle posteriorly translated during knee flexion for both osteoarthritic and healthy knees (Figure 5). This posterior translation was rapid in the initial 40 degrees and then more gradual. However, downhill walking showed paradoxical anterior translation in the first 40 degrees of flexion.

3.6 Projection of the femoral-condylar axis above the tibia

Seven studies reported kinematics by projecting the femoral-condylar axis above the reference tibia (Table 2). The activities examined were squat, step-up, lunge and knee positioning in supine, and side lying. The three papers reported the same participants performing a squat, but different axes: geometric-centre axis (GCA) (Mochizuki 2013), transepicondylar axis (TEA) above the tibia (Mochizuki 2014), and the vertical distance of the TEA above the tibia (Mochizuki 2015) (Appendix). Saari 2005 and Weidow 2006 divided the participants into those with medial or lateral osteoarthritis.

Synthesis:

Meta-analysis was not performed. Plots of these data showed that for both osteoarthritis and healthy knees, the position of the medial-femoral-condylar axis above a reference tibial plateau showed the medial axis moving anteriorly for the first 40 to 60 degrees of flexion, then remaining in place or translating posteriorly (Figure 6). There was no particular pattern observed for knees with osteoarthritis. For the studies with a control group, the shapes of curves for medial-axis translation very similar for healthy and osteoarthritic knees. However, during step-up, lunge and squat osteoarthritic knees began more posteriorly and remained more posterior than the healthy knees. In contrast, during a deeper squat the geometric-centre axis stayed slightly anterior (Mochizuki 2013). In lateral compartment osteoarthritis the medial-femoral axis moved more anteriorly during flexion (Weidow 2006), but in medial compartment osteoarthritis the medial femoral axis did not appear to translate anteriorly (Saari 2005).

For both osteoarthritic and healthy knees, the position of the lateral-femoral-condylar axis above a reference tibial plateau showed posterior translation during flexion (Figure 7). In studies with a control group the lateral axis was positioned more anteriorly for the knees with osteoarthritis, except for the lunge activity. Medial or lateral compartment osteoarthritis did not affect projections of the lateral-femoral-condylar axis.

4. Discussion

This systematic review aimed to identify and analyse the published research to define the characteristics of knee kinematics in knees with osteoarthritis that deviate from healthy kinematics. Meta-analysis was precluded because of the diversity measurement systems, reporting systems and activities. However, visual representations of the data demonstrated that osteoarthritic knees have a more adducted position throughout flexion, have a more anterior contact pattern in the lateral compartment throughout flexion, and a more anterior projection of the lateral-femoral-condylar axis above the tibia.

Meta-analysis was prevented by the diversity of methods used by research teams. Within each study there were close associations between kinematics of OA and healthy participants but between studies there were wide differences due to the diversity in the activities and the reference systems used for kinematic analysis. Broadly, the three main reference systems included 6 degrees of freedom, contact patterns, and projection of the femoral-condylar axis above a reference tibia. Within each system there was variation in origins and axes. For example, a 9-degrees variation in tibial (internal) rotation between the transepicondylar axis (4.8 degrees) and geometric-centre axis (13.8 degrees) has been described (Most et al. 2004). Similarly, projection of the femoral-condylar axes above the tibial plateau can vary by as much as 13 to 50 mm depending on the axes chosen for analysis (Walker et al. 2011). Use of the femoral-condylar or transepicondylar axis may result in variations of 4.6° (range, 1.8° to 11.3°) (Eckhoff et al. 2005). Comparison of study results requires consensus regarding the mechanical axes of the femur and the origins of the planes. Such standardisation will facilitate higher-level synthesis of research evidence in this field and facilitate future meta-analyses.

To measure kinematics in 6 degrees of freedom, reference axes need to be established for the femur and tibia. The femoral axes were commonly established by setting the flexion axis of the femur (y) through the centres of spheres matched to the posterior-femoral condyles (GCA), the mechanical axis (x) intersecting the midpoint of the femoral-condylar axis with the femoral head, and the anteroposterior axis (z) was the cross-product (Farrokhi 2016). Variations of this method set the femoral condylar axis through the centres of circles fitted to the posterior-femoral condyles instead of spheres (FFC, Appendix) (Saari 2005, Weidow 2006) or by setting to the transepicondylar axis (TEA). Furthermore, the long axis of the femur may be set to the anatomical axis (shaft of the femur) (Yue 2011, Li 2015) or the mechanical axis (head of femur). There can be 5-10 degree difference between the mechanical and anatomical axis of the femur (Hollister et al. 1993). The tibial reference axes tended to me more consistent, with the mediolateral-tibial axis (y-axis) defined by the line connecting the most medial and lateral points of the tibial plateau. The mechanical axis (x-axis) was defined by the perpendicular bisector of the medial-lateral axis and a line drawn to the centre of the ankle joint (Farrokhi 2012). These comparisons demonstrate the wide variation between study methods that preclude comparison between osteoarthritic and healthy arthrokinematics.

Different activities resulted in a range of arthrokinematic patterns (Hamai 2009, Fiacchi 2014), demonstrating the task-dependence of kinematics. However, the overall association between flexion and internal rotation was relatively consistent. The arthrokinematics of the knee are derived partly by the architecture of the knee (Blankevoort et al. 1988) and partly by the forces arising from muscles and external forces (Andriacchi 2006). One contrasting activity was downhill walking (Farrokhi 2012, Farrokhi 2014, Gustafson 2015, Farrokhi 2016), potentially because it was an anterior centre of gravity, or eccentric quadriceps activity. Therefore, it appears that knee arthrokinematics in flexion is activity dependent.

Overall, there appeared to be reduced translation in the lateral compartment of knees with osteoarthritis. This was demonstrated by the anterior position of the projection of the lateral-condylar axis. While the comparative anterior position of the lateral axis could be interpreted as external rotation (Saari 2005, Scarvell 2007, Kawashima 2013), we did not observe external rotation in the 6-degrees-of-freedom studies (Yue 2011), and neither did a thorough motion-analysis systematic review (Mills 2013). While Mills examined the effects progression of arthritis on arthrokinematics, this systematic review included medial, lateral, and bi-compartmental osteoarthritis of all grades. This may have cancelled out some of the observed effects. With standardisation of analysis methods, future studies might be able to examine progression of osteoarthritic on kinematics including rotation.

The participants in the reviewed studies had predominantly medial-compartment osteoarthritis, so it would have been reasonable to expect kinematic changes in the medial contact pattern, or medial-femoral axis projection. Instability in the medial kinematics may account for this. Farrokhi (2014) found the medial contact point excursions were longer with self-reported instability and that contact-point velocity was greater. Similarly, Gustafson et al. 2015 found that unstable knees had greater variability in sagittal-plane movement of medial contact points.

This systematic review should be interpreted in the light of its limitations. First, heterogeneity of study design precluded statistical meta-analysis so synthesis relied on graphical plots of arthrokinematics Therefore, interpretation should be cautious. A future systematic review may consider combining two papers for meta-analysis when a contemporaneous control group is included. Second, the included studies were weak in terms of risk of bias, the limited use of contemporaneous control participants and small sample sizes with lack of power. The number of papers with contemporaneous comparison of osteoarthritic and healthy knees was small and some were dependent on historical control groups. This made them vulnerable to changes in technology, methods, and the execution of activities with resultant effects on the arthrokinematics recorded. All of the studies had small sample sizes, probably due to the technical complexity and reliance on imaging with radiation-exposure risk. This meant that they were under-powered to detect clinically-important differences.

However, some interesting observations have been made regarding this significant body of literature. As this field of research matures, the study design is expected to become more robust, and more opportunities to pool and compare data will emerge.

In conclusion, despite being unable to conduct a statistical meta-analysis, a number of important observations concerning the effect of osteoarthritis on knee arthrokinematics have emerged. Healthy knees and knees with osteoarthritis both internally rotate during flexion. Knees with osteoarthritis maintain a more adducted position, particularly from 0 to 90 degrees of flexion, and the projection of the lateral-femoral axis above the tibia remains more anterior than healthy knees, though this is not necessarily to be interpreted as external rotation. It is strongly recommended standardisation of reference axes and methods of analysis are required for this field of research to progress.

Acknowledgements

The authors would like to thank Cara Lewis and Jing-Sheng Li at College of Health and Rehabilitation Science, Boston University, Boston Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts, for extracting the data on osteoarthritic participants from their study on knee kinematics in obesity to allow it to be presented here.

Conflict of Interest Statement.

The authors have no conflicts of interest.

References

Akter, M., Lambert, A. J., Pickering, M. R., Scarvell, J. M. and Smith, P. N., 2015. Robust initialisation for single-plane 3D CT to 2D fluoroscopy image registration. Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization 3, 147-171.

Alta, T. D. W., Miller, D., Coghlan, J., Troupis, J. M. and Bell, S., 2012. The new 4D CT scanner allows dynamic visualization and measurement of acromio-clavicular joint motion. Journal of Bone & Joint Surgery 94-B, 28-28.

Andriacchi, T. P. and Mundermann, A., 2006. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. Current Opinion in Rheumatology 18, 514-518.

Arthritis Research UK, 2017. State of Musculoskeletal Health 2017. Arthritis & other musculoskeletal conditions in numbers. Chesterfield, UK.

Australian Institute of Health and Welfare, 2015. Hospitalisation and the treatment of osteoarthritis. Canberra, AIHW.

Blankevoort, L., Huiskes, R. and De Lange, A., 1988. The envelope of passive knee joint motion. Journal of Biomechanics 21, 705-720.

DeFrate, L. E., Papannagari, R., Gill, T. J., Moses, J. M., Pathare, N. P. and Li, G., 2006. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency - An in vivo imaging analysis. American Journal of Sports Medicine 34, 1240-1246.

Dimitriou, D., Tsai, T.-Y., Park, K. K., Hosseini, A., Kwon, Y.-M., Rubash, H. E. and Li, G., 2016. Weight-bearing condyle motion of the knee before and after cruciate-retaining TKA: In-vivo surgical transepicondylar axis and geometric center axis analyses. Journal of Biomechanics 49, 1891-1898.

Downs, S. H. and Black, N., 1998. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. Journal of Epidemiology and Community Health 52, 377–384.

Eckhoff, D. G., Bach, J. M., Spitzer, V. M., Reinig, K. D., Bagur, M. M., Baldini, T. H. and Flannery, N., 2005. Three-Dimensional Mechanics, Kinematics, and Morphology of the Knee Viewed in Virtual Reality. Journal of Bone & Joint Surgery 87-A, 71-80.

Farrokhi, S., Tashman, S., Gil, A. B., Klatt, B. A. and Fitzgerald, G. K., 2012. Are the kinematics of the knee joint altered during the loading response phase of gait in individuals with concurrent knee osteoarthritis and complaints of joint instability? A dynamic stereo X-ray study. Clinical Biomechanics 27, 384-389.

Farrokhi, S., Voycheck, C. A., Gustafson, J. A., Fitzgerald, G. K. and Tashman, S., 2016. Knee joint contact mechanics during downhill gait and its relationship with varus/valgus motion and muscle strength in patients with knee osteoarthritis. Knee 23, 49-56.

Farrokhi, S., Voycheck, C. A., Klatt, B. A., Gustafson, J. A., Tashman, S. and Fitzgerald, G. K., 2014. Altered tibiofemoral joint contact mechanics and kinematics in patients with knee osteoarthritis and episodic complaints of joint instability. Clinical Biomechanics 29, 629-635.

Farrokhi, S., Voycheck, C. A., Tashman, S. and Fitzgerald, G. K., 2013. A biomechanical perspective on physical therapy management of knee osteoarthritis. Journal of Orthopaedic & Sports Physical

Therapy 43, 600 - 691.

Fiacchi, F., Zambianchi, F., Digennaro, V., Ricchiuto, I., Mugnai, R. and Catani, F., 2014. In vivo kinematics of medial unicompartmental osteoarthritic knees during activities of daily living. Knee 21, S10-S14.

Fregly, B., 2012. Gait modification to treat knee osteoarthritis. Hospital for Special Surgery Journal 8, 45-48.

Fregly, B., Banks, S., D'Lima, D. and Colwell, C., 2008. Sensitivity of knee replacement contact calculations to kinematic measurement errors. Journal of Orthopaedic Research 26, 1173-1179.

Gustafson, J. A., Robinson, M. E., Fitzgerald, G. K., Tashman, S. and Farrokhi, S., 2015. Knee motion variability in patients with knee osteoarthritis: The effect of self-reported instability. Clinical Biomechanics 30, 475-480.

Haladik, J. A., Vasileff, W. K., Peltz, C. D., Lock, T. R. and Bey, M. J., 2014. Bracing improves clinical outcomes but does not affect the medial knee joint space in osteoarthritic patients during gait. Knee Surgery Sports Traumatology and Arthroscopy 22, 2715-2720.

Hamai, S., Moro-oka, T. A., Miura, H., Shimoto, T., Higaki, H., Fregly, B. J., Iwamoto, Y. and Banks, S. A., 2009. Knee kinematics in medial osteoarthritis during in vivo weight-bearing activities. Journal of Orthopaedic Research 27, 1555-1561.

Hamai, S., Okazaki, K., Ikebe, S., Murakami, K., Higaki, H., Nakahara, H., Shimoto, T., Mizu-Uchi, H., Akasaki, Y. and Iwamoto, Y., 2016. In Vivo Kinematics of Healthy and Osteoarthritic Knees During Stepping Using Density-Based Image-Matching Techniques. Journal of Applied Biomechanics 32, 586-592.

Higgins, J. P. T., Altman, D. G., Gøtzsche, P. C., Jüni, P., Moher, D., Oxman, A. D., Savović, J., Schulz, K. F., Weeks, L. and Sterne, J. A. C., 2011. The Cochrane Collaboration’s tool for assessing risk of bias in randomised trials. British Medical Journal 343, d5928.

Hodges, P. W., van den Hoorn, W., Wrigley, T. V., Hinman, R. S., Bowles, K. A., Cicuttini, F., Wang, Y. and Bennell, K., 2016. Increased duration of co-contraction of medial knee muscles is associated with greater progression of knee osteoarthritis. Manual Therapy 21, 151-158.

Hollister, A., Jatana, S., Singh, A., Sullivan, W. and Lupichuk, A., 1993. The axes of rotation of the knee. Clinical Orthopaedics and Related Research 290, 259-268.

Hurwitz, D. E., Sharma, L. and Andriacchi, T. P., 1999. Effect of knee pain on joint loading in patients with osteoarthritis. Current Opinion in Rheumatology 11, 422-426.

Karrholm, J., Brandsson, S. and Freeman, M., 2000. Tibiofemoral movement 4: changes in axial rotation caused by forced rotation at the weight-bearing knee studied by RSA. Journal of Bone & Joint Surgery 82-B, 1201-1203.

Kaufman, K. R., Hughes, C., Morrey, B. F., Morrey, M. and An, K.-N., 2001. Gait characteristics of patients with knee osteoarthritis. Journal of Biomechanics 34, 907-915.

Kawashima, K., Tomita, T., Tamaki, M., Murase, T., Yoshikawa, H. and Sugamoto, K., 2013. In vivo three-dimensional motion analysis of osteoarthritic knees. Modern Rheumatology 23, 646-652.

Kitagawa, A., Ishida, K., Chin, T., Tsumura, N. and Iguchi, T., 2014. Partial restoration of knee kinematics in severe valgus deformity using the medial-pivot total knee arthroplasty. Knee Surgery Sports Traumatology Arthroscopy 22, 1599-1606.

Kitagawa, A., Tsumura, N., Chin, T., Gamada, K., Banks, S. A. and Kurosaka, M., 2010. In Vivo Comparison of Knee Kinematics Before and After High-Flexion Posterior Cruciate-Retaining Total Knee Arthroplasty. Journal of Arthroplasty 25, 964-969.

Koga, Y., 2015. Three-dimensional motion analysis and its application in total knee arthroplasty: what we know, and what we should analyze. Journal of Orthopaedic Science 20, 239-249.

Lewek, M. D., Rudolph, K. S. and Snyder-Mackler, L., 2004. Control of frontal plane knee laxity during gait in patients with medial compartment knee osteoarthritis. Osteoarthritis Cartilage 12, 745-751.

Li, C., Hosseini, A., Tsai, T. Y., Kwon, Y. M. and Li, G., 2015. Articular contact kinematics of the knee before and after a cruciate retaining total knee arthroplasty. Journal of Orthopaedic Research 33, 349-358.

Li, G., DeFrate, L. E., Sang, E. P., Gill, T. J. and Rubash, H. E., 2005. In vivo articular cartilage contact kinematics of the knee: An investigation using dual-orthogonal fluoroscopy and magnetic resonance image-based computer models. American Journal of Sports Medicine 33, 102-107.

Li, J.-S., Tsai, T.-Y., Felson, D. T., Li, G. and Lewis, C. L., 2017. Six degree-of-freedom knee joint kinematics in obese individuals with knee pain during gait. Plos One 12.

Mills, K., Hunt, M. A. and Ferber, R., 2013. Biomechanical deviations during level walking associated with knee osteoarthritis: A systematic review and meta-analysis. Arthritis Care and Research 65, 1643-1665.

Mochizuki, T., Sato, T., Blaha, J. D., Tanifuji, O., Kobayashi, K., Yamagiwa, H., Watanabe, S., Matsueda, M., Koga, Y., Omori, G. and Endo, N., 2014. Kinematics of the knee after unicompartmental arthroplasty is not the same as normal and is similar to the kinematics of the knee with osteoarthritis. Knee Surgery Sports Traumatology Arthroscopy 22, 1911-1917.

Mochizuki, T., Sato, T., Tanifuji, O., Kobayashi, K., Koga, Y., Yamagiwa, H., Omori, G. and Endo, N., 2013. In vivo pre- and postoperative three-dimensional knee kinematics in unicompartmental knee arthroplasty. Journal of Orthopaedic Science 18, 54-60.

Mochizuki, T., Sato, T., Tanifuji, O., Kobayashi, K., Yamagiwa, H., Watanabe, S., Koga, Y., Omori, G. and Endo, N., 2015. Unicompartmental knee arthroplasty cannot restore the functional flexion axis of a living knee to normal. Knee Surgery Sports Traumatology Arthroscopy 23, 3736-3742.

Most, E., Axe, J., Rubash, H. and Li, G., 2004. Sensitivity of the knee joint kinematics calculation to selection of flexion axes. Journal of Biomechanics 37, 1743-1748.

Pickering, M. R., Scarvell, J. M. and Smith, P. N., 2009. An Improved Ct to Fluoroscopy Registration Algorithm for the Kinematic Analysis of Knee Joints. 2009 16th International Conference on Digital Signal Processing, Vols 1 and 2, 183-+.

Saari, T., Carlsson, L., Karlsson, J. and Karrholm, J., 2005. Knee kinematics in medial arthrosis. Dynamic radiostereometry during active extension and weight-bearing. Journal of Biomechanics 38, 285-292.

Scarvell, J., Pickering, M. and Smith, P., 2008. A new technique for registration of 2D x-ray fluoroscopy to 3D CT data for the analysis of knee kinematics. 68th Australian Orthopaedic Association Annual Scientific Meeting. Hobart.

Scarvell, J. M., Smith, P. N., Refshauge, K. M. and Galloway, H. R., 2007. Magnetic resonance imaging analysis of kinematics in osteoarthritic knees. Journal of Arthroplasty 22, 383-393.

Sharma, G. B., Saevarsson, S. K., Amiri, S., Montgomery, S., Ramm, H., Lichti, D. D., Lieck, R., Zachow, S. and Anglin, C., 2012. Radiological method for measuring patellofemoral tracking and tibiofemoral kinematics before and after total knee replacement. Bone & Joint Research 1, 263-271.

Sharma, L., Song, J., Felson, D., Cahue, S., Shamiyeh, E. and Dunlop, D., 2001. The role of knee alignment in disease progression and functional decline in knee osteoarthritis. Journal of the American Medical Association 286, 188-792.

Simic, M., Hinman, R. S., Wrigley, T. V., Bennell, K. L. and Hunt, M. A., 2011. Gait modification strategies for altering medial knee joint load: A systematic review. Arthritis Care & Research 63, 504-426.

Walker, P. S., Heller, Y., Yildirim, G. and Immerman, I., 2011. Reference axes for comparing the motion of knee replacements with the anatomic knee. Knee 18, 312-316.

Weidow, J., 2006. Lateral osteoarthritis of the knee. Etiology based on morphological, anatomical, kinematic and kinetic observations. Acta Orthopaedica Supplement 77, 3-44.

You, B.-M., Siy, P., Anderst, W. and Tashman, S., 2001. In vivo measurement of 3-D skeletal kinematics from sequences of biplane radiographs: Application to knee kinematics. IEEE Transactions on Medical Imaging 20, 514-525.

Yue, B., Varadarajan, K. M., Moynihan, A. L., Liu, F., Rubash, H. E. and Li, G., 2011. Kinematics of Medial Osteoarthritic Knees before and after Posterior Cruciate Ligament Retaining Total Knee Arthroplasty. Journal of Orthopaedic Research 29, 40-46.

Zeighami, A., Dumas, R., Kanhonou, M., Hagemeister, N., Lavoie, F., de Guise, J. A. and Aissaoui, R., 2017. Tibio-femoral joint contact in healthy and osteoarthritic knees during quasi-static squat: A bi-planar X-ray analysis. Journal of Biomechanics 53, 178-184.

Zeni, J. and Higginson, J., 2009. Dynamic knee joint stiffness in subjects with a progressive increase in severity of knee osteoarthritis. Clinical Biomechanics 24, 366–371.

Figure Legends

Box 1. Design of the systematic review.

Box 2. Inclusion and exclusion criteria for selection of studies.

Box 3. Recommendations for future studies in knee kinematics.

Table 1. Methodological quality of included studies, assessed by a Modified Downs and Black checklist (Downs and Black, 1998).

Table 2. Data extraction from studies for systematic review.

Figure 1. Flow chart of papers included in the systematic review.

Figure 2. Kinematics of internal and external rotation in healthy knees and those with and osteoarthritis (symbols indicate papers).

Figure 3. Kinematics of abduction and adduction in healthy knees and those with and osteoarthritis (symbols indicate papers).

Figure 4. Kinematics recorded by tibiofemoral contact points in the medial compartment of healthy knees and those with and osteoarthritis (symbols indicate papers).

Figure 5. Kinematics recorded by tibiofemoral contact points in the lateral compartment of healthy knees and those with and osteoarthritis (symbols indicate papers).

Figure 6. Kinematics recorded by projection of the femoral flexion axis above the medial tibia of healthy knees and those with and osteoarthritis (symbols indicate papers).

Figure 7. Kinematics recorded by projection of the femoral flexion axis above the lateral tibia of healthy knees and those with and osteoarthritis (symbols indicate papers).

Appendix. Derivation of the flexion axis of the femur by the geometric centre axis (A), transepicondylar axis (B) or flexion facet centre axis (C).

Design of included studies:

Descriptive, observational, quasi-experimental, experimental studies, randomised controlled trials or systematic reviews.

Participants:

Participants will have knees with osteoarthritis. Osteoarthritis may include medial or lateral compartments or both.

Interventions:

Descriptions of knee motion by analysis of bony motion using medical imaging technologies. Medical imaging may include fluoroscopy, dynamic MRI or CT, ultrasound, radiofrequency instrumentation, or any other mechanism for determining the position of the bones or joint surfaces.

Motion could be captured by any functional activity including but not limited to gait, lunge or squat, open chain leg extension, or stepping.

Outcome measures:

Descriptions of knee motion by analysis of bony motion using medical imaging technologies, reported using any of system of recording, such as six degrees of freedom, tibiofemoral contact patterns, or centres of femoral motion.

Comparisons:

Kinematics of knees with osteoarthritis were compared to knees of healthy populations.

Assessment of quality of studies:

Modified Downs and Black assessment criteria (1998).

Quality of studies was not an exclusion criterion.

Box 1. Design of the systematic review.

Inclusion criteria:

Observational studies of knees with osteoarthritis

May or may not include comparison with healthy participants.

Intervention studies that have recorded the motion of knees with osteoarthritis prior to surgery

Report descriptive quantitative data

May record kinematics by

- 6 degrees of freedom
- Medial-lateral femoral condyle translation
- Tibio-femoral contact patterns
- Other measures of joint motion

Exclusion criteria:

Do not include any quantitative data

Reviews without new data

Healthy participants only

In vitro only

Patello-femoral joint only

Post surgery participants only

Gait/motion analysis by surface markers or video only

Finite Element Analysis only

Animal studies.

Box 2. Inclusion and exclusion criteria for selection of studies.

Recommendations

1 Design includes a contemporaneous control group. Methods change so fast, as technologies change, that data collected from a control group years ago is not valid.

2 Design includes matched control participants, preferably matched for age, gender and BMI to account for those covariates.

3 Design separates participants with medial from lateral compartment osteoarthritis as they may exhibit different kinematics.

4 Consensus in reached between research centres on an agreed referencing system for biomechanical analysis, to include setting the axes. In the meantime, consider complete reporting of methods regarding how axes were derived, how origins were set and how data were normalised to account for size of the knee.

Box 3. Recommendations for future studies in knee kinematics.

Figure 1. Flow chart of papers included in the systematic review.

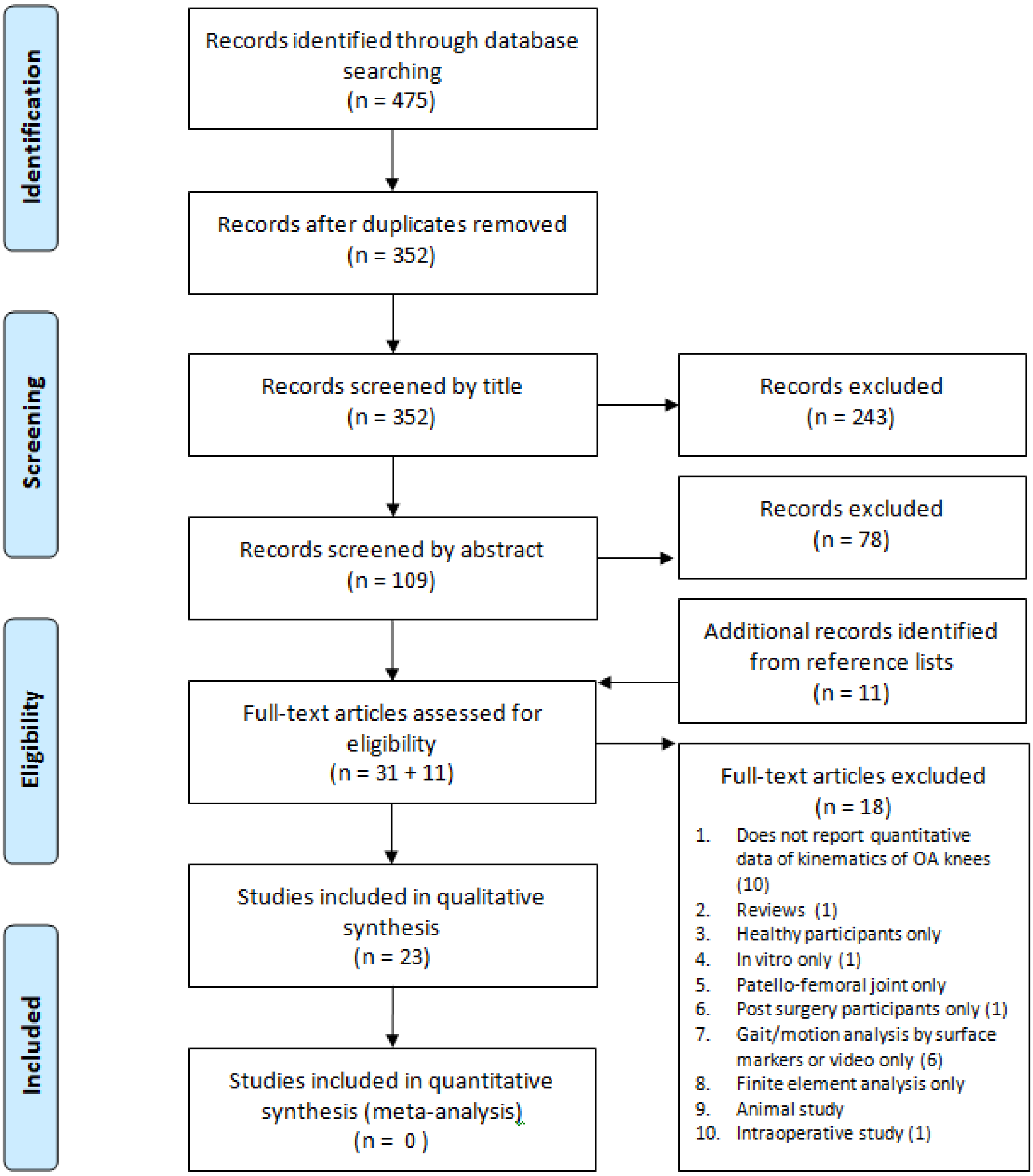


Figure 2. Kinematics of internal and external rotation in healthy knees and those with and osteoarthritis (symbols indicate papers).

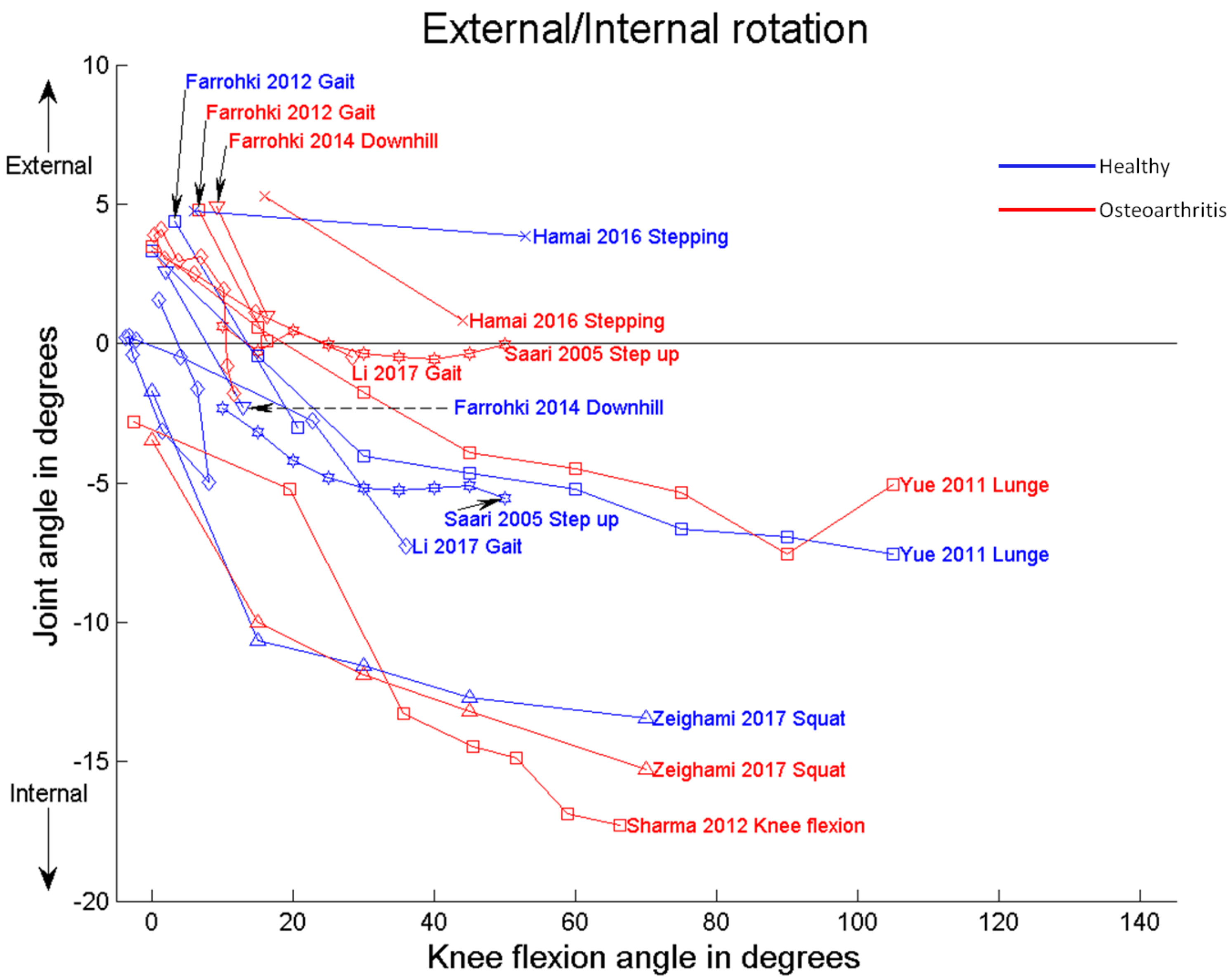


Figure 3. Kinematics of abduction and adduction in healthy knees and those with and osteoarthritis (symbols indicate papers).

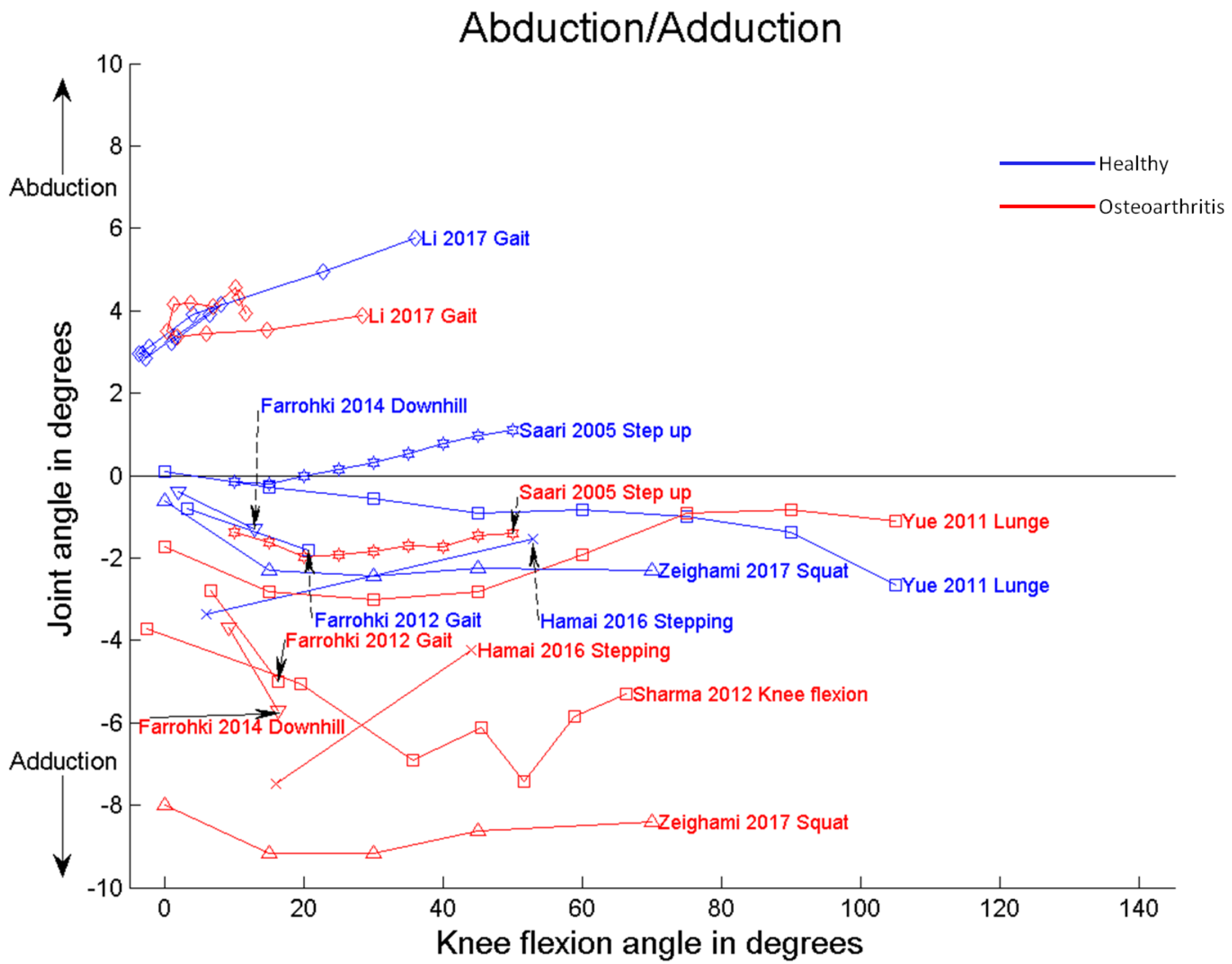


Figure 4. Kinematics recorded by tibiofemoral contact points in the medial compartment of healthy knees and those with and osteoarthritis (symbols indicate papers).

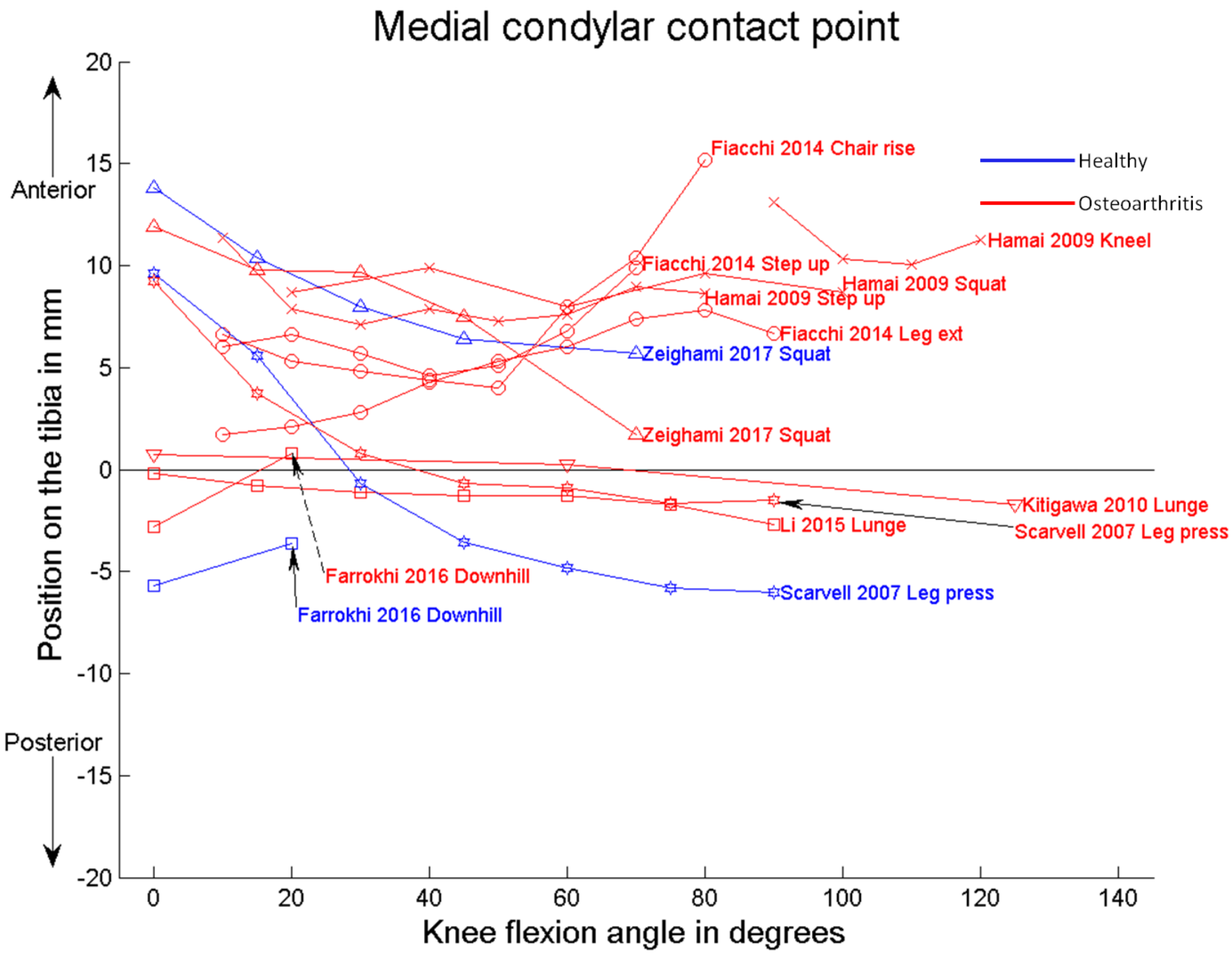


Figure 5. Kinematics recorded by tibiofemoral contact points in the lateral compartment of healthy knees and those with and osteoarthritis (symbols indicate papers).

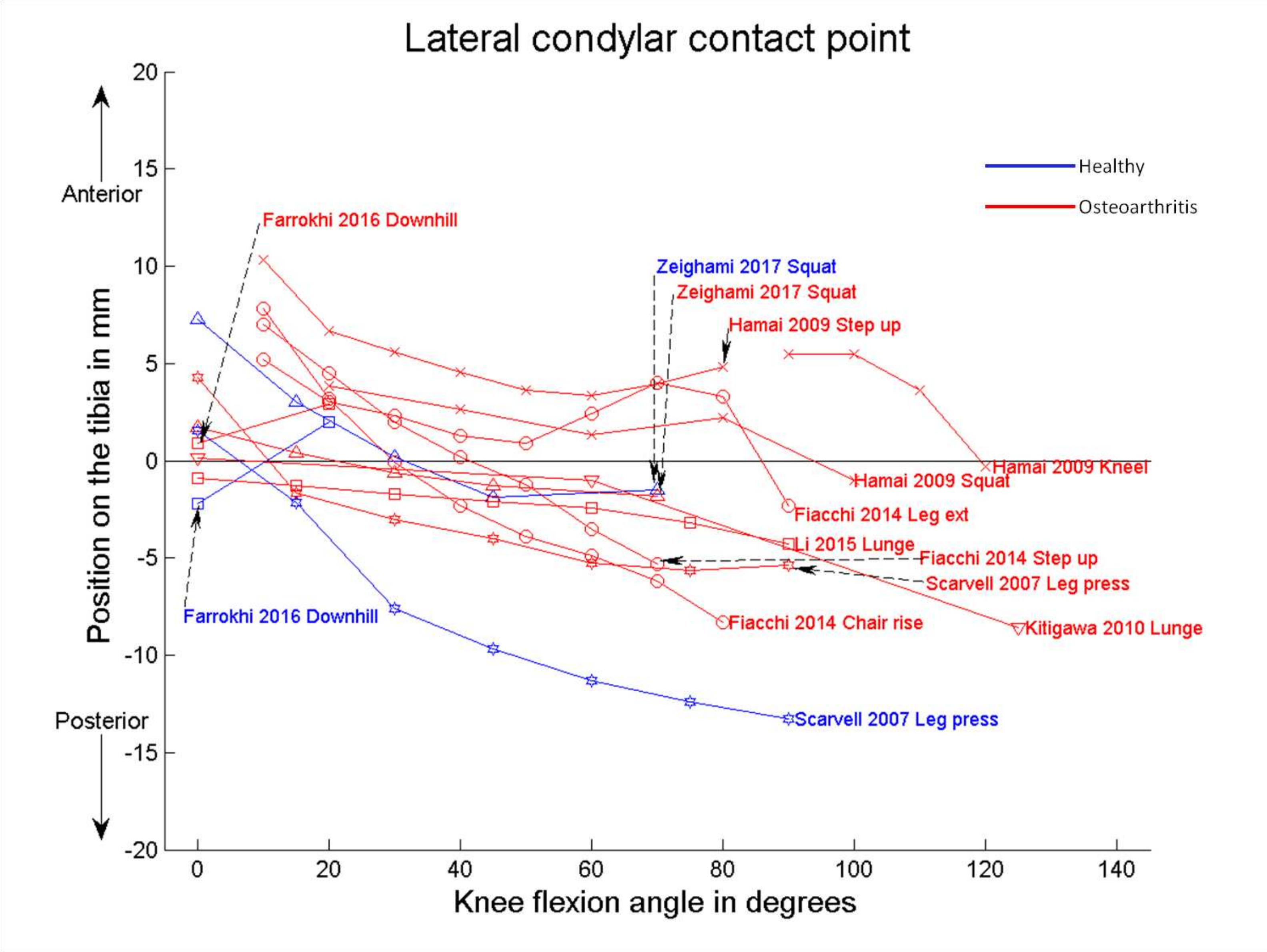


Figure 6. Kinematics recorded by projection of the femoral flexion axis above the medial tibia of healthy knees and those with and osteoarthritis (symbols indicate papers).

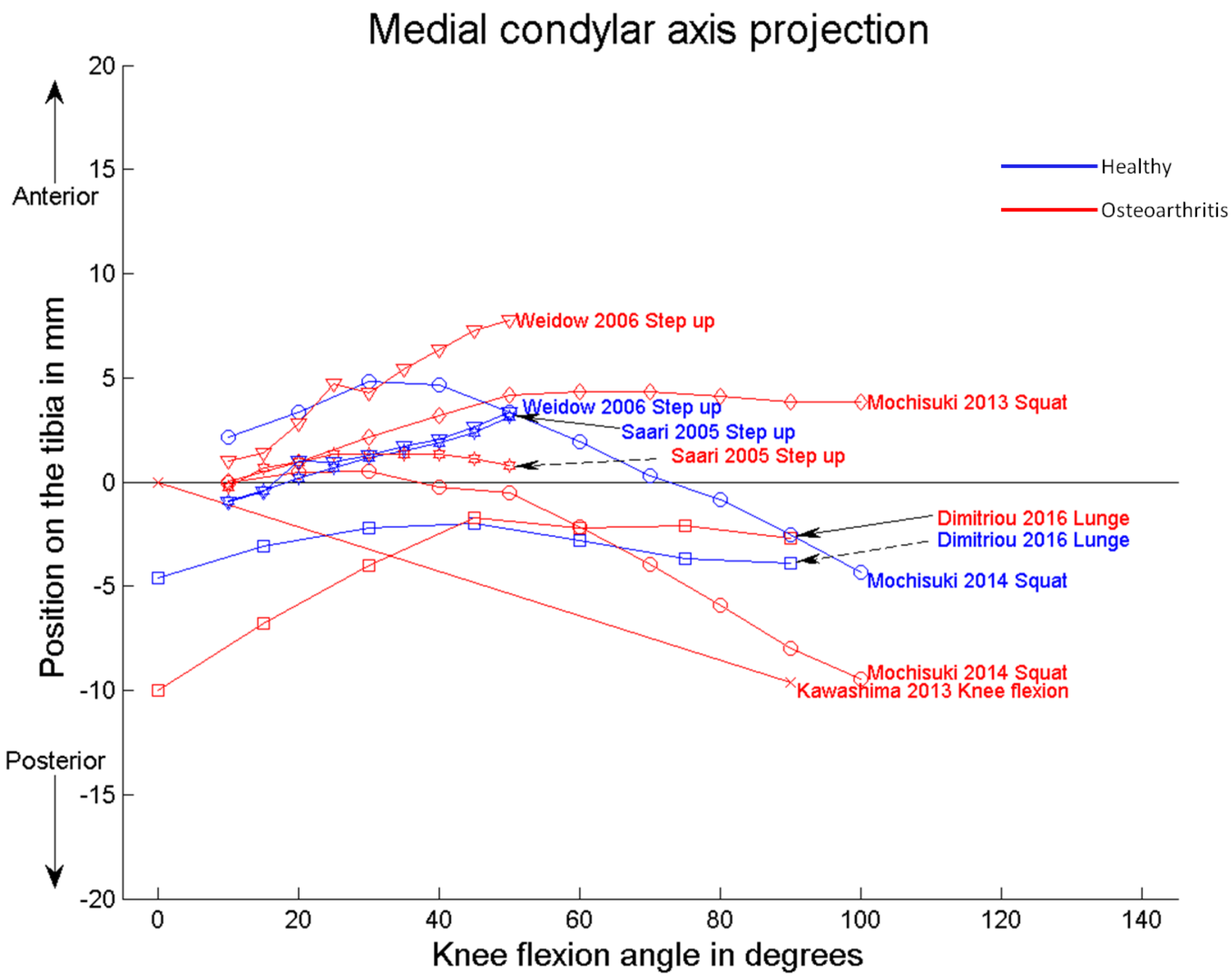
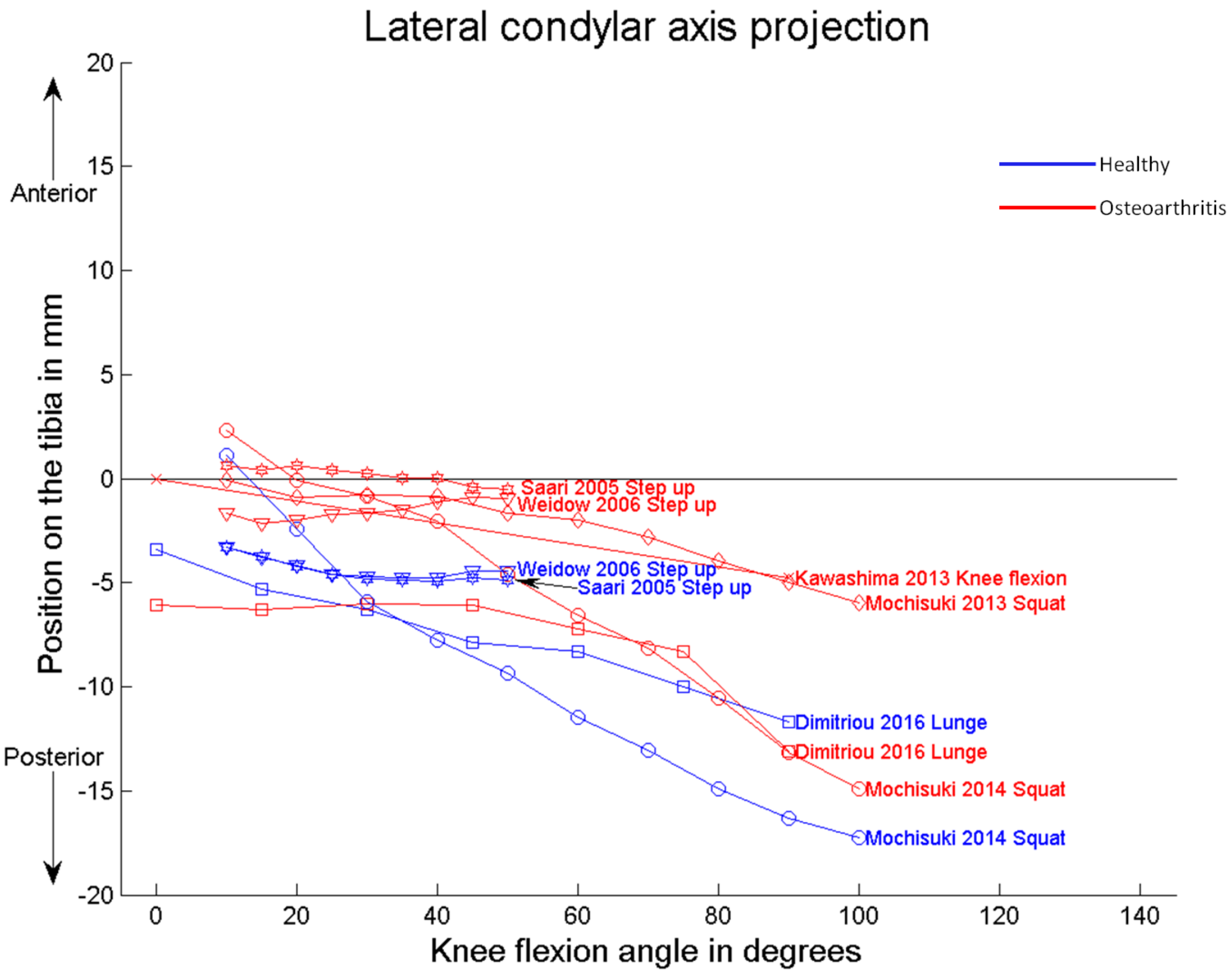


Figure 7. Kinematics recorded by projection of the femoral flexion axis above the lateral tibia of healthy knees and those with and osteoarthritis (symbols indicate papers).



Downs and Black Items:	Clear aim	Clearly stated outcomes	Participant inclusion and exclusion criteria	Intervention clearly described	Confounders described	Clear findings	Variability in data provided	Participants represent population	Appropriate statistical analysis	Outcomes valid & reliable	Cases & controls from same population	Participants randomised	Powered for MCID
	Reporting							**External validity**	**Internal Validity (Bias)**		**Internal Validity (selection bias)**		**Power**
Dimitriou, 2016	Y	Y	In part	Y	In part	Y	Y	?	N	Y	N	N	N
Farrokhi, 2012	Y	Y	Y	Y	Y	Y	Y	?	N	Y	Y	N	N
Farrokhi, 2016	Y	Y	Y	Y	Y	Y	Y	?	Y	Y	Y	N	N
Fiacchi, 2014	Y	Y	Y	Y	In part	Y	Y	?	N	Y	na	na	N
Gustafson 2015	Y	Y	Y	Y	Y	Y	In part	?	Y	Y	Y	N	N
Haladik, 2014	Y	Y	Y	Y	Y	Y	Y	?	Y	Y	na	N	Y
Hamai, 2009	Y	Y	Y	Y	Y	Y	Y	?	Y	Y	na	N	N
Hamai, 2016	Y	Y	Y	Y	Y	Y	In part	?	N	Y	N	N	N
Kawashima 2013	Y	Y	N	Y	In part	Y	Y	?	N	Y	na	na	N

Kitagawa, 2010	Y	Y	Y	Y	In part	Y	Y	?	N	Y	na	na	N
Kitagawa, 2014	Y	Y	N	Y	In part	Y	Y	?	N	Y	na	na	N
Li C, 2015	Y	Y	N	Y	In part	Y	Y	?	Y	Y	na	na	N
Li J-S, 2017	Y	Y	Y	Y	Y	Y	Y	?	N	Y	N	N	N
Mochizuki, 2013	Y	Y	Y	Y	N	Y	Y	?	N	Y	N	N	N
Mochizuki, 2014	Y	Y	N	Y	N	Y	Y	?	N	Y	N	N	N
Mochizuki, 2015	Y	Y	N	Y	N	Y	Y	?	N	Y	N	N	N
Saari, 2005	Y	Y	N	Y	N	Y	Y	?	N	Y	N	N	N
Scarvell, 2007	Y	Y	Y	Y	N	Y	Y	?	N	Y	N	N	N
Sharma, 2012	Y	?	N	Y	In part	Y	Y	?	N	Y	na	na	N
Weidow, 2006	Y	Y	N	Y	N	Y	Y	?	N	Y	N	N	N

Yue, 2011	Y	Y	Y	Y	Y	Y	Y	?	N	N	N	N	N
Zeighami, 2017	Y	Y	N	Y	Y	Y	Y	?	N	Y	N	N	N

Y Yes, this criterion is met.

N No this criterion is not met.

? Unclear, partially met, or unable to determine.

na Not applicable for this study design.

Table 1. Methodological quality of included studies, assessed by a Modified Downs and Black checklist (Downs and Black, 1998).

Table 2. Data extraction from studies for systematic review.

Study	OA Participants	Healthy Participants	Study Design	Activity Captured	Method of Analysis	Findings for knees with osteoarthritis
Dimitriou, 2016	n = 11 age 61 (4) years 7M, 4F height 1.74 (.09) m weight 94 (14) kg 'advanced medial OA, scheduled for arthroplasty' no-clinical score	n = 8 ages 31 (9) years 5M, 3F height 1.70 (.10) m weight 75 (14) kg	Quasi experimental non equivalent, historical control group (Qi 2013) Pre-post surgery	Lunge quasi static imaged at 15-degree intervals, still	Single fluoroscopy registered to MRI Analysed as: Projection of femoral axis above the tibia (TEA and GCA: AP and height)	At extension the OA medial and lateral axes commenced more posteriorly above the tibia than the controls (5.6mm, 9.3mm respectively), but by 40 degrees flexion this difference was gone.
Farrokhi, 2012	n = 14 all 14 unstable. 6M, 8F M OA n=7 M+L OA n=7 age: M OA 68 (10), M+L OA 69 (6) years height: M OA 1.73 (.11), M+L OA 1.69 (.08) m weight: M OA 93 (20), M+L OA 82 (6) kg BMI: M OA 31 (6), M+L OA 29 (3) kgm^{-2}	n = 12 ages 70 (8) years 6M, 6F height 1.73 (.13) m weight 77 (20) kg BMI 25 (5) kgm^{-2} clear x-rays	Quasi experimental Contemporaneous control Matched for age, sex BMI different	Downhill walking Loading phase of gait on a treadmill Dynamic movement, recorded @ 100Hz	Biplanar x-ray registered to CT (DSX) Analysed as: 6DoF: 3 rotations, AP, ML translation	M and M+L OA had less flexion and less internal rotation excursion than controls ($p<0.01$). Total ab/adduction ROM was increased. ($p<0.05$). AP translation was not different between any groups.
Farrokhi 2014	n = 18: stable n = 7, unstable n = 11 age stable 71 (9) years, unstable 70 (8) stable 1M,6F, unstable 5M,6F BMI stable 30 (7), unstable 32 (5) kgm^{-2} KL grades: stable median 3, unstable median 4	n = 25 ages 70 (7) years 12M, 13F BMI 25 (4) kgm^{-2} KL grades: 0	Quasi experimental Contemporaneous control Matched for age, sex BMI different	Downhill walking Loading phase of gait on a treadmill Dynamic movement, recorded @ 100Hz	Biplanar x-ray / CT (DSX) Analysed as: 6DoF: 3 rotations and 3 translations And angular velocity contact point velocity contact point excursion	Medial contact point excursions were longer in the unstable group (v stable($p=0.05$), control ($p=0.02$). Peak medial contact point velocity was greater for the unstable group (v stable ($p=0.05$), controls ($p=0.02$). Unstable knees had a coupled movement pattern of knee extension and external rotation after heel contact which was different to the knee flexion and internal rotation demonstrated by stable and control groups.
Farrokhi, 2016	n = 11 age 70 (8) 3M, 8F height 1.68 (.09) m weight 86 (14) BMI 30 (5) kgm^{-2} Primary medial OA of KLII or more.	n = 11 age 68 (5) 5M, 6F height 1.77 (.13) m weight 77 (12) BMI 25 (3) kgm^{-2}	Quasi experimental Contemporaneous control Matched for age Different BMI, height	Downhill walking Loading phase of gait on a treadmill Dynamic movement, recorded @ 100Hz	Biplanar x-ray / CT (DSX) Analysed as: 6DoF: angular velocity contact point velocity contact point	OA knees had larger M-L contact point excursions ($p=0.02$), greater heel-strike M-L contact point velocities ($p=0.02$), increased adduction excursions($p=0.02$), and weaker quads and hip abductors ($p=0.03$) than control group knees. Increased contact point excursions & velocities

Table 2. Data extraction from studies for systematic review.

Study	OA Participants	Healthy Participants	Study Design	Activity Captured	Method of Analysis	Findings for knees with osteoarthritis
					excursion	were associated with adduction excursion
Fiacchi, 2014	n = 8 age 70 (8) 4M, 4F Primary medial OA Ahlback grades all (3-4)		Descriptive Cross sectional.	Chair rise, step up, open chain leg extension. Dynamic movement	Single fluoroscopy / CT Analysed as: Contact map AP motion of the contact point Contact-line rotation	Comparison was between activities, no control group. Tibia internally rotated with flexion in all tasks. Greatest internal rotation of tibia was seen in weight-bearing tasks. OA knees had no external rotation in screw home.
Gustafson, 2015	n = 19: stable n=8, unstable n= 11 age stable 69 (8); unstable 70 (8) 1M,7F; 5M,6F height: stable 1.72 (.15); unstable 1.72 (.10) m weight: stable 81 (12), unstable 93 (16) BMI: stable 28 (5), unstable 32 (5) kgm^{-2} KL grades: stable 1@2, 5@3,2@4 unstable 2@2,3@3,6@4	n = 24 ages 70 (8) 9M, 13F height 1.74 (.12)m weight 75 (16) kg BMI 25 (4) kgm^{-2} KL grade: 22@0, 2@1	Quasi experimental case control study Contemporaneous control Matched for age, sex, height Different BMI	Downhill walking Loading phase of gait on a treadmill Dynamic movement continuous @ 100Hz	Biplanar x-ray / CT (DSX) Analysed as: 6DoF: motion variability for 3 rotations, AP and ML translation & contact pattern	Stable knees had less sagittal-plane motion variability than controls (p=0.04), Unstable knees had more sagittal-plane motion variability than controls (p=0.003) and stable knees (p <0.001). Unstable knees had more A-P contact point motion variability at the medial compartment than controls (p= 0.03) and stable groups (p= 0.03). While OA knees generally had less variability and less excursion, knees with OA and instability have more variability.
Haladik, 2014	n = 10 age 60 (7) years 9M, 1F clinical score WOMAC		Descriptive Same day pre-test, post-test.	Treadmill walking Dynamic movement continuous With, without knee brace120Hz	Biplanar x-ray / CT Analysed as: 6DoF (mean total) Contact pattern and Functional joint space; medial and lateral joint contact centre	Wearing the brace improved WOMAC scores by 33%, but made no differences to joint space, 6DoF kinematics or contact pattern.
Hamai, 2009	n = 12 age 74 (8) years 1M, 11F height 1.51 (.08) m weight 60 (13) kg KL grade 3.9 (0.3) (1 @ grade 3, 11@4) KSS 58 (9); 56 (9)		Descriptive Cross sectional.	Kneel, squat, step up Dynamic movement 3 Hz	Single fluoroscopy / CT Analysed as: 6DoF and contact patterns	Medial OA knees internally rotated during flexion with a medial pivot pattern, like healthy knees. Medial OA knees had overall more tibial external rotation bias than healthy knees. Classic screw-home movement into extension was not seen. Differences in rotation and contact patterns were seen between different activities.
Hamai, 2016	n = 14 age 74 (62-74) years	n = 6 age 30 (29-33)years	Quasi experimental Contemporaneous,	Stepping in place; divided into 6 phases	Single fluoroscopy / CT	OA knees had less knee extension (p=0.02), more varus angle (p=0.03), less posterior

Table 2. Data extraction from studies for systematic review.

Study	OA Participants	Healthy Participants	Study Design	Activity Captured	Method of Analysis	Findings for knees with osteoarthritis
	14F height 1.46 (1.34-1.58)m weight 59 (45-81) kg BMI 28 (23-37) kgm^{-2} KL grade 3@3; 11@4	6M height 1.72 (1.65-1.77) m weight 68 (59-80) kg BMI 24 (18-28) kgm^{-2}	non-equivalent, case control study	Dynamic movement - 10 Hz divided by 6 phases of 'gait'	Analysed as: 6DoF: valgus, varus, rotation; varus thrust, and weight bearing ratio.	translation (p=0.04) and larger medial shift (p=0.03) during stepping than controls. Internal rotation was not significantly different.
Kawashima 2013	n = 15 ages 74 (4) 3M, 12F KL grade 3@3, 1@4 KSS 42 (15), 49 (14)		Descriptive Correlational,	Knee position 0, 90 and max flex Static position captured in supine or side lying	CT still image Flexion estimate from the static position Analysed by: Projection of the TEA above the tibia	From 0 to 90^0 flexion, 11 tibias externally and 4 internally rotated. From 90^0 to maximum flexion, all tibias internally rotated. The epicondylar axis moved backward in all (but one) knees, but the medial epicondyles moved 1 mm more backward than the lateral epicondyles. Rotation was assoc. with flexion (r= -0.42). Compared to healthy, the OA knees lost normal tibial internal rotation with flexion.
Kitagawa, 2010	n = 10 age 74 years (65-79) gender 2M, 8F		Quasi experimental Pre-post surgery	Lunge (weight bearing deep flexion to Max flex.) dynamic continuous	Single Fluoroscopy / CT Analysed by: Projection of the cylindrical femoral axis above the tibia; contact pattern	OA knees had small posterior femoral translation and limited axial rotation.' Pre-operatively, axis projection moved 1 (2mm back in medial and 9 (1mm back in lateral compartment.
Kitagawa, 2014	n = 7: OA n=5, RA n=2 age 74 years (65–79) 5F		Quasi experimental Pre-post surgery	Lunge (quasi static) Dynamic measured at intervals - frames at 60,90 Maximum flexion	Single Fluoroscopy / CT Analysed by: Projection of the cylindrical femoral axis above the tibia contact pattern as closest point	OA knees had paradoxical external rotation of tibia 4.7 (7.6)º into flexion (healthy would internally rotate) and the projected axis moved 6.9 (9.7) mm back in the medial compartment, and 3.9 (13.8) mm back in the lateral compartment (n.s.).
Li C, 2015	n = 11 age 64 (7) height 1.74 (.10)m weight 94 (15 KL grade 4@3, 7@4		Quasi experimental Pre-post surgery	Lunge Dynamic movement	Dual fluoroscopy / MRI Analysed by: Contact points AP and ML	For OA knees from 0 degrees to full flexion, medial translated posteriorly by 11 (6) % and lateral contact points by 16 (5)%.
Li J.-S, 2017	Obese n = 10 age 43 (10) years 2M, 8F height 1.66 (.09) m	n = 8 32-49 years BMI 24 (18-28) kgm^{-2}	Quasi experimental non equivalent, historical control group (Kozanek 2009)	Treadmill walking Dynamic movement 30 frames/s	Dual fluoroscopy / MRI Analysed by:	Obese individuals with knee pain maintained the knee in more flexion (p=0.02), anterior tibial translation (p=0.01) and adduction (p<0.001) during most of the stance phase of the gait

Table 2. Data extraction from studies for systematic review.

Study	OA Participants	Healthy Participants	Study Design	Activity Captured	Method of Analysis	Findings for knees with osteoarthritis
	weight 11013 BMI 40 (3) kgm^{-2} Subset of OA n = 4 KL grade 2 clinical score WOMAC				6DoF 3 rotations, 3 translations.	cycle and had a reduced total range of knee flexion (p=0.002) compared to a healthy non-obese group.
Mochizuki, 2013	n = 14 patients (17 knees) age 75 (6) years BMI 25 (5) kgm^{-2} KL grade 5 knees@3, 12@4 KSS 56 (10); Function 43 (21)		Quasi experimental non equivalent, historical control group (Tanifuji 2013) Pre-post surgery	Squat from stand to maximum flexion Dynamic movement 15 frames /s	Single fluoroscopy / CT Analysed by: Projection of the geometric centre axis (GCA) above the tibia.	OA knees from 10 to 100 degrees flexion had near-constant (tibial internal rotation, 14 (8) degrees) and anterior translation of the medial GCA (4 (5) mm) and posterior translation of the lateral GCA (6 (6) mm).
Mochizuki, 2014	n = 17 age 77 (62–82) BMI 25.6 (18.7–28.9) kgm^{-2} KL grade 4 (3–4)		Quasi experimental non equivalent, historical control group (Tanifuji 2013) Pre-post surgery	Squat from stand to maximum flexion Dynamic movement 15 frames /s	Single fluoroscopy / CT Analysed by: Projection of the Transepicondylar axis (TEA) above the tibia	(reported AP locations and translations). OA knees had less tibial internal rotation (p=0.04), more posterior position of the medial end of the TEA (p=0.03), more anterior position of the lateral TEA (p=0.03) than controls.
Mochizuki, 2015	n = 14 patients (17 knees) age 75 (6) BMI 25(3 kgm^{-2} KL grade 3.7 (0.5) KSS 56 (10), 43 (21)		Quasi experimental non equivalent, historical control group (Tanifuji 2013) Pre-post surgery	Squat from stand to maximum flexion Dynamic movement 15 frames /s	Single fluoroscopy / CT Analysed by: Projection of the TEA above the tibia	(reported superior locations and translations). The medial end of the TEA, from 10° to 100° flexion, healthy and OA had superior vertical translation of 7.3 (4.2) and 4.3 (7.2) mm respectively (n.s.).
Saari, 2005	n = 14 age 62 years (50–73) 6M, 8F Ahlback 4@1, 5@2, 2@3 and 2@4, 1@grade 5	n = 10 age 26 (16-41) years gender - no details	Quasi experimental Contemporaneous non-equivalent control group - case control	Step up on 16 cm box Dynamic, asked to move slowly, frames 2-4/s	Biplanar x-ray- RSA Analysed by: Projection of the Flexion facet centres above the tibia AP, ML translation and rotation	OA knees had decreased internal tibial rotation (0.5 degrees, compared to 5.6 degrees, p=0.02), corresponding to less posterior displacement of the lateral femoral flexion facet centre between 50 and 20 of extension (p=0.08). The midpoint between the two tips of the tibial intercondylar eminence occupied a more posterior position within the range of motion analysed (p=0.03)
Scarvell, 2007	n = 14 age 65 (9) years	n = 12 age 20 to 50	Quasi experimental non equivalent,	Supine leg press Quasi static	MRI still Analysed by:	Contact points in both medial and lateral compartments moved back less in OA than

Table 2. Data extraction from studies for systematic review.

Study	OA Participants	Healthy Participants	Study Design	Activity Captured	Method of Analysis	Findings for knees with osteoarthritis
	3M, 11F KL grade 1@2, 5@3, 8@4	gender 7M, 5F	historical control group (Scarvell 2004)	measured at 15 degree intervals	Contact patterns	controls (medial 5mm less, lateral 6mm less. p<0.01).
Sharma, 2012	n = 3 age 60 (5) years 3F		Descriptive is a methods validation study (OA and post op pts)	Knee flexion quasi static measured at intervals -place foot onto platform of different heights.	Dual fluoroscopy / CT Analysed by: 6DoF: 3 rotations, 3 translations	Findings relate to reliability and accuracy, not to difference between healthy and OA. Accuracy 0.9mm and 0.6 degrees.
Weidow, 2006	n = 5 age 70 (62–74) years 1M, 4F Ahlbäck 3; (3–4)	n = 11 age 26 (16–41) years 8M, 3F	Quasi experimental non equivalent, historical control group (Saari 2005) OA vs intact side of ACL- people	Step up on 16cm box Dynamic movement 2-4 frames /sec	Biplanar x-ray- RSA Analysed by: Projection of the Flexion facet centres (FFC) above the tibia AP, ML translation and rotation	Knees with lateral OA had increased anterior translation of the medial FFC which at 45° was 4–5 mm more than in the healthy knees (p=0.03). There was no difference with the lateral FFC, or rotation. Lateral OA knees were more valgus (2 – 3 degrees, p=0.01).
Yue, 2011	n = 11 ages 64 (7) years 7M,4F height 1.73 (.10) m weight 94 (15) kg KL grade 4@3, 7@grade4 KSS 55 (13); 50 (20)	n = 22 age 31 (9) years 12M, 10F height 1.73(.10)m weight 76 (14) kg	Quasi experimental non equivalent, historical control group (Varadarajan 2009) Pre-post surgery	Lunge to max flex. Single leg. quasi static, images captured at 15 degree intervals, pts asked to keep still	Dual fluoroscopy / MRI Analysed by: 6DoF: 3 rotations, 3 translations	OA knees had similar internal tibial rotation to controls (n.s.). In OA knees the femur was located more medially than controls, at between 30◦ and 60◦ flexion (p=0.05). OA knees had less posterior femoral translation between 0◦ and 105◦ flexion (p=0.01), more adduction between 0◦ and 45◦ flexion (p=0.02), than controls.
Zeighami, 2017	n = 9 ages 61 (9) years 2M, 7F height 1.63 (0.12)m weight 89 (15)kg BMI 33 (7) kgm^{-2} KL grade - all KL 4	n = 10 ages 55 (17)years 6M, 4F height 1.67 (0.17)m weight 69 (20) kg BMI 25 (5) kgm^{-2}	Quasi experimental case controlled, contemporaneous matched for age, height BMI different	Squat quasi static measured at intervals - sit on a stool at set height	Analysed by: 6DoF: 3 rotations, 3 translations and contact pattern	OA knees had greater adduction angles (p=0.01) and femur located medially relative to the tibia (p=0.01). Contact points of lateral condyles moved back less (10 (8) mm, control, and 4 (3) mm OA). Average contact point locations on the medial and lateral tibial plateaus of the OA patients were shifted (6.5 (.7) mm) medially compared controls.

Abbreviations:

OA: osteoarthritis, M: male, F: female, ACL: anterior cruciate ligament, KL: Kellgren Lawrence grade for osteoarthritis, AP: antero-posterior, ML: mediolateral, KSS: American Knee Society

Score, BMI: body mass index, NWB: non-weight-bearing, 6DoF: Six Degrees of Freedom, FFC: flexion facet centre, GCA: geometric centre axis, TEA: transepicondylar axis, RSA: roentgen photogrammetric analysis, n.s. not significant.

Notes:

1. Data are reported as mean (standard deviation) where available, or mean (range) otherwise.
2. Tibiofemoral internal/external rotation is defined as the rotation of the tibia against the femur. Where authors have reported this as femoral rotation, this has been changed to be consistent across this review.
3. Varus and tibial adduction are considered synonymous